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There are two parts to this research program. First program focusses on the quantification of loosely held concepts such as "structure," and "dynamic significance" of structure in the study of turbulent flows in general, and shear flows in particular. We have developed a robust algorithm which "extracts" regions of concentrated activity in a fluctuating turbulence variable and labels each region individually for quantitative and graphical analysis, and applied the technique to the combined visual and quantitative analysis of vorticity, strain-rate, Reynolds stress and turbulent kinetic energy in the transition for isotropic to shear-dominated homogeneous turbulence. The focus of the second program is on interscale interactions in high Reynolds number turbulence, with a particular focus on the direct interaction between large and small scales in the dynamic evolution of equilibrium and nonequilibrium turbulent flows. Analytical analysis has demonstrated the persistence of these interactions in the high Reynolds number limit and basic analysis of the limiting triadic form of the Navier-Stokes equation has appeared in several publications. Based on predictions made from the asymptotic triadic equations, we have analysed the dynamics of direct large-small scale couplings through direct numerical simulations of initially isotropic turbulence forced anisotropically at the large scales and found that large scale restructuring can dramatically alter small scale structure and dynamics.

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TURBULENCE STRUCTURE ASSOCIATED WITH INTERCOMPONENT AND INTERSCALE ENERGY TRANSFER, and MODIFICATION BY FORCING

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Abstract

There are two parts to this research program. The emphasis of the first program is on the quantification of loosely held concepts such as "structure," and "dynamic significance" of structure in the study of turbulent flows in general, and shear flows in particular. We have developed a robust algorithm which "extracts" regions of concentrated activity in a fluctuating turbulence variable and labels each region individually for quantitative and graphical analysis. The methodology is applied to the analysis of the dynamical relationships among vorticity, strain-rate, Reynolds stress and turbulent kinetic energy in the transition for isotropic to shear-dominated homogeneous turbulence. Once extracted, the intermittent regions are ordered in terms of the intensity of the fluctuations within the region. The relative contributions, characteristics, and interrelationships among low-to-high intensity regions are then simultaneously quantified and visualized. Considerable analysis has been carried out of the transition from isotropic to shear-dominated turbulence through direct numerical simulations using a pseudo-spectral algorithm which has, to date, appeared in one published paper and a Ph.D. thesis.

The focus of the second program of research is on interscale interactions in high Reynolds number turbulence in terms of triadic interactions within Navier-Stokes evolution. In particular, we focus on the direct interaction between large and small scales in the dynamic evolution of equilibrium and nonequilibrium turbulent flows. Analytical analysis has demonstrated the persistence of these interactions in the high Reynolds number limit (ie, infinite scale separation), and basic analysis of the limiting triadic form of the Navier-Stokes equation in Fourier-space has appeared in several publications. Based on predictions made from the asymptotic triadic equations, we have analysed the dynamics of direct large-small scale couplings through direct numerical simulations of initially isotropic turbulence forced anisotropically at the large scales. We have found that large scale restructuring can dramatically alter small scale structure and dynamics and have reported many important dynamical details in two publications.

I. PARTICIPATING RESEARCHERS

Supported from the grant (partially or fully)

- Prof. James G. Brasseur — Principal Investigator.
- Wen-quei Lin — Ph.D. Candidate: received Ph.D. 8/93. He is now employed with Analysis and Design Application Co. (ADAPCO), Long Island, New York).

- Dr. P.K. Yeung — Research Associate, 12/89-3/92 (took up a faculty position at Georgia Tech. in March 1992). Partial support from this grant.
- Dr. Lian-Ping Wang — Research Associate, 9/92-present. Supported for 1 year in part with leftover funds from AFOSR-89-0026. Continues with partial support from ARO grant on Atmospheric Turbulence.

Unsupported from this grant, but carrying out related analyses

- Chao-hsuan Wei — M.S. student; (partial support one semester from URI/AFOSR grant AFOSR-90-0113). Received M.S. degree 8/91 (currently working for a company in Taiwan)
- Brian Moquin — Ph.D. student, supported for three years under URI/AFOSR grant AFOSR-90-0113. Beginning 8/93 is supported through an A.R.O. AASERT grant.
- Qunzhen Wang — Ph.D. Candidate (full support from URI/AFOSR grant AFOSR-90-0113). Completed his Ph.D. requirements in February, 1994.

II. RESEARCH OBJECTIVES

This program had two overall overall objectives:

1. **The development and application of a methodology to objectively extract local concentrations of turbulence variables.**
   - Kinematic and dynamic characteristics coherent structural elements at the large energetic scales vs. at the small vorticity and strain-rate dominated scales of motion.
   - Concurrent visual and statistical analysis of small-scale structural elements.
   - General effects of shear on turbulence structure and dynamics. Analysis of the local processes associated with the creation of anisotropic shear-dominated turbulence from isotropic turbulence.

2. **Analysis of interscale dynamics in high Reynolds number turbulence through the triadic couplings of the Navier-Stokes equation.**
   - Fundamental physics of scale interactions in high Reynolds number turbulence analyzed through the triadic structure of the Navier-Stokes equation in the Fourier-spectral view.
   - Emphasis on the interactions between the large energetic scales of motion and the small vortical and dissipative scales of motion.
   - Issues of nonequilibrium vs. equilibrium turbulence, large-small-scale independence, and local isotropy.
   - Concurrent physical and Fourier-space views of turbulence evolution and dynamics, and the structural relationship between physical and Fourier-space.

III. RESEARCH SUMMARY

A. The development and application of a methodology to objectively extract local concentrations of turbulence variables.

(W-Q. Lin, J.G. Brasseur)

Approach

The emphasis of this study was on the quantification and analysis of loosely held concepts such as "structure," "scale," and "dynamic significance" of intermittent regions within turbulent flows in general, and shear flows in particular. We refer to the volumetric regions containing intense activity in a turbulent variable as "intermittent structures," or "events." The approach is based on the development of a robust algorithm which "extracts" intermittent structures in a fluctuating turbulence variable and labels each structure individually for quantitative and graphical analysis. In this study the methodology is applied in the analysis of the dynamical relationships among vorticity, strain-rate and Reynolds shear stress in the transition from isotropic to shear-dominated homogeneous turbulence. Once identified, the intermittent structures are ordered according to characteristics of interest and analysed in various ways using both statistical measures and graphical analysis. In most cases, the intermittent structures are ordered in this study according to a measure of intensity. In this way, the relative contributions of intermittent structures to turbulence statistics, characteristics of intermittent structures, and interrelationships among low-to-high intensity intermittent structures may be quantified as a function of the relative levels of activity within the event. At the same time, the interstitial regions outside the intermittent events are available for analysis of the characteristics of low-level background fluctuations.

Summary of the Analyses

Probability density functions (pdf) of turbulence variables indicate that the global mean of a turbulence variable is dominated by low-magnitude fluctuation of order one rms, and that the high intensity intermittent contributions to the pdf contribute very little to the global statistics. The manner in which pdf statistics are constructed, however, is such to remove any coherence within localized regions of intense activity. By contrast, we find that the intermittent structures in the vorticity, strain-rate and Reynolds stress fields are the *dominant* contributors to the turbulence statistics and that the high intensity events are structurally distinct from the low-level fluctuations surrounding them. By visualizing these structures at different time, it appears that the well-formed events live for several large-scale time scales, indicating strong coherence.

Kinematically, we find that the vorticity and strain-rate fields display structural similarity in the highest intensity events. The more intense vorticity events are dominated by negative spanwise vorticity fluctuations and are the primary contributors both to the non-Gaussian nature of the vorticity field and the anisotropy of the vorticity-vorticity correlation tensor. The more intense strain-rate events align with the mean flow in a way which maximized their interactions with the mean strain-rate and with the fluctuating vorticity.

The strongest Reynolds shear stress events contain almost entirely negative uv fluctuations, indicating that these events are the dominant contributors to turbulence production in the shear flow. Furthermore, these high intensity Reynolds shear stress events exist with equal probability within the second and forth quadrants of the $u-v$ joint pdf in the homogeneous flow, in contrast with wall-bounded shear flow where Q2 events predominate near the wall. In the inertial layer of the turbulent boundary layer, however, Khanna and Smith (as part of the AFOSR-sponsored joint URI with our group and that of Lex Smits at Princeton) have shown that the $u-v$ joint pdf is again balanced between the second and forth quadrants, like the homogeneous flow. The implication is that blockage effects at the wall produces a bias towards the second quadrant events which disappears away from the wall in an inertia-dominated regions which, in some respects, is similar to homogeneous shear flow.

Using a carefully conducted simulation of the transition from isotropic to shear-dominated homogeneous turbulence, the effects of the mean shear on the evolution and dynamics of the vorticity and strain-rate fields were studied. The transition in both global and local statistics were analyzed to identify those processes which produce the global characteristics of vorticity and strain-rate observed in all shear flows. We find that the fluctuating vorticity and strain-rate fields evolve simultaneously toward an asymptotic state in two distinct temporal periods, and initial transient period of adjustment to the imposition of shear, followed by an asymptotic period of continuous change. An effect of shear is to enhance the alignment between the vorticity and strain-rate fields, which improves both the correlation between the vorticity and strain-rate, and the correlation between vorticity production and strain-rate production, as the strain-rate fluctuations approach a locally two-dimensional structure. Vorticity and strain-rate alignment appears to occur indirectly, in that both vorticity and strain-rate tend to align independently with the mean strain-rate tensor. The consequence is an alignment between vorticity and strain-rate fluctuations, which also maximizes the production of vorticity and strain-rate through interactions with mean shear.

To quantify the dynamic effects of the mean shear on the small-scale structure, the evolutionary characteristics of vorticity and strain-rate events under shear were analyzed. Event size, event intensity and the relative contributions from high intensity events to turbulence statistics all increase as a consequence of mean shear. Whereas tube- and sheet-like structures are still the dominant structural shapes in the vorticity and strain-rate fields, vorticity and strain-rate events tend to flatten under shear. Most importantly, the production of vorticity and strain-rate through turbulence-turbulence interactions occurs *at the peripheries* of vorticity and strain-rate events. This result suggests that a vortex model of small-scale turbulence based on the continual straining of vortex tubes in the regions of maximal vorticity (such as the Burgers vortex model, for example) is not appropriate for this generic shear flow.

To analyze the dynamical evolution of individual vortex structures, a prototypical vorticity event was followed in time and analyzed both graphically and quantitatively. Our primary interest was to develop some understanding of the dynamical processes leading to the creation and evolution of the hairpin vortex, the prototypical vortex structure found in *all* shear flows. However, evolutionary studies of this type are notoriously difficult to perform, because of the need for time-resolved three-dimensional data of several variables and, more importantly, because of the need for sophisticated analytical tools which allow the user to interactively extract, visualize and quantify attributes of particular structures within the complex tangles web of small-scale turbulence. This analysis was accomplished within a special-purpose highly interactive visualization-based "analytical environment," developed under a companion AFOSR-sponsored URI program at Penn State. Even with this state-of-the-art tool, however, the evolutionary analysis of single events was found to be a very time-consuming process. Consequently, it was only possible to analyze a single hairpin vortex event in detail.

We chose a particularly well-formed hairpin vortex extracted half way through the simulation, then followed the vortex backwards and forwards in time. We found that this particular vorticity event evolves from a well-defined vortex sheet in the isotropic initial state to a coherent hairpin vortex after the application of mean shear. The topology of the concentrated regions of vorticity changed rapidly to form first a flattened vortex tube within elliptical cross section, before distorting into a hairpin at later time. Various parts of the hairpin evolved differently, the head, for example, having more of a vortex sheet-like structure and the legs a tube-like structure. Most importantly, we found that as the extracted vortex changes its topological form, so did the vorticity and strain-rate production dynamics within the vortex. Indeed, the change in topology and local geometry of the vortex was found to be directly correlated with changes in the local dynamical processes taking place within the structure. We conclude based on this one detailed study that the kinematic and dynamic evolution of localized events within the turbulent shear flow are closely linked.

Importance and Applications

It is clear from this comprehensive study the intermittent regions of fluctuating vorticity, strain-rate and Reynolds shear stress play important, if not dominant roles in the kinematic and dynamic development fo shear turbulence. Whereas a great deal of knowledge has been gained concerning the local structure and dynamics of vorticity, strain-rate, and Reynolds shear stress events in turbulence, and the effect of shear on these regions, globally this study has shown clearly that the kinematic structure and local dynamics of turbulence are closely related. Furthermore, the effect of shear, we find, is to modify both the structure and the dynamics of the regions of primary turbulence activity. These modifications, though complex, underlie the global evolution of turbulence in general and turbulent shear flows in particular, including wall-bounded and free shear flows found in most technological applications. Modeling strategies which attempt to capture local as well as global details of the flow must properly characterize the more important dynamical processes within the more prevalent structural features, such as hairpin vortices. These dynamical processes involve interactions among the primary structures within the turbulence and interactions with the mean, which itself modifies the structural interactions within the turbulence.

B. Analysis of interscale dynamics in high Reynolds number turbulence through the triadic couplings of the Navier-Stokes equation.

(J.G. Brasseur, P.K. Yeung, C-H. Wei, L-P. Wang)

Approach

Much work has been carried out towards the analysis of the triadic structure of the Navier-Stokes equation in the high Reynolds number limit. This work has been reported in a number of publications and manuscripts, including a paper to appear in February 1994 in the *Physics of Fluids* by Brasseur & Wei, and a paper currently under review for *J. Fluid Mech.* by Yeung, Brasseur & Wang. Two manuscripts (by Zhou, Yeung & Brasseur, and by Wang & Brasseur) are under preparation which have continued these studies in new directions, and a related manuscript by Vassilicos, Moquin & Brasseur begins to address issues of high Reynolds number small-scale structure and scale similarity. The essence of these works is the unraveling of interscale dynamics in terms of scale separation, location within the spectrum, and triadic structure in Fourier space and, more recently, the corresponding local dynamics in physical space.

Results of Yeung, Wei and Brasseur:
Basic Studies of Triadic Scale Interactions in Equilibrium and Non-equilibrium Turbulence

Much interesting and far-reaching knowledge has come from this program of study. A great deal of study, for example, has centered on the effect of large, energy-containing eddies on the smallest, most dissipative scales in a high Reynolds number turbulent flow. We learn that, in principle, a coupling exists and that this coupling intensifies with scale separation. Consequently it is possible, in principle, for small scales to be directly stimulated by the stimulation of large eddies. On the other hand, more local and nonlocal interactions act to remove information from the larger scales on the smallest scales. Which effect wins out depends on the global state of the flow, and its history. Turbulence in an equilibrium state has established an energy cascade within is internally in a local equilibrium state. In such a state, the net effect of local cascading processes apparently overwhelm the direct couplings between large and small scales, although recent evidence still suggests a significant role for these couplings. We have clearly shown, however, that when the turbulence is in a transitional, or nonequilibrium state, direct large-small scale interactions can be stimulated and can, over finite periods of time, dominate small scale dynamics.

The details of these studies are given in three manuscripts, two which have been published in the *Physics of Fluids*, and one which is under review by *J. Fluid Mech.* This work continues in a recent manuscript by Zhou, Yeung & Brasseur soon to be submitted to the *Physics of Fluids.*

Recent Analysis of L-P. Wang and J.G. Brasseur:
Contribution of Long-range Interactions to Small-scale Phase Changes in Isotropic Turbulence

Small-scale turbulence evolution involves the redistribution of both energy and phase among high wavenumber Fourier modes. Previous studies have shown that distant triadic interactions strongly couple large-scale to small-scale evolution in coherently forced homogeneous turbulence in a manner consistent with the asymptotic form of the triadic equations. Here we analyse the role of distant triadic interactions on the *phase changes* at the small scales in *isotropic* decaying turbulence. To this end, parameters are defined which describe the relative magnitudes and orientations of the Fourier coefficients of high wavenumber modes, and the average time rates of change of phase are analysed for individual triadic interactions as a function of scale separation. We find that the distant triadic group is, by far, the dominant contributer to the changes in phase at the small scales, a result consistent with the forced simulations of Yeung, Brasseur and Wang (1994).

This study was presented at the APS meeting in Alburquerque, November 1993 and is being written up for submittal to a journal.

Importance and Applications

The implications of these studies is far reaching and rather profound. The results suggest, for example, that turbulence closures which are to be applied in high Reynolds number turbulence which experience nonequilibrium transitional states, should include direct couplings between large and small scales if small scale dynamics plays a role in the processes of interest. Furthermore, these studies suggest that the details of small scale processes, mixing for example, may be altered or controlled via changes made at the large scales, through changes in the boundary conditions, for example. Finally, these studies add considerable depth to the simplistic description of turbulent energy cascade and the underlying hypotheses proposed by Kolmogorov in 1941, and leave open a rich field of new possibilities in our understanding of turbulence which demands further exploration.

IV. PAPERS AND ABSTRACTS

A. Papers and Manuscripts

Zhou, Y., Yeung, P.K. & Brasseur, J.G. 1994 Scale disparity and spectral transfer in anisotropic numerical turbulence. Manuscript nearly complete, soon to be submitted to *Phys. Fluids.*

Vassilicos, J.C., Moquin, B.P., Brasseur, J.G. 1994 Self-similar spiral flow structure in low Reynolds number isotropic and decaying turbulence. under review, *J. Fluid Mech.*

Wang, Q., Brasseur, J.G., Smith, R.W., Smits, A.J. 1994 Multi-dimensional continuous wavelet transforms and applications to turbulence data. under review, *Proc. Royal Soc. London A.*

Brasseur, J.G. & Wei, C-H. 1994 Interscale dynamics and local isotropy in high Reynolds number turbulence within triadic interactions. *Phys. Fluids* **6** (2): 842-870.

Lin, W-Q. 1993 Structural and dynamical characteristics of intermittent structures in homogeneous turbulent shear flow. Ph.D. Thesis, Department of Mechanical Engineering, Pennsylvania State University.

Yeung, P.K., Brasseur, J.G. and Wang, Q. 1993 Dynamics of large-to-small scale couplings in coherently forced turbulence: concurrent physical and Fourier-space views. under review, *J. Fluid Mech.*.

Brasseur. J.G., Wang, Q. 1992 Structural evolution of homogeneous turbulence at different scales analysed using 3D wavelet transforms. *Phys. Fluids A* **4**: 2538-2554.

Wei, C-H. 1991 Interscale Couplings and Spectral Dynamics in High Reynolds Number Turbulence in terms of Triadic Interactions. M.S. Thesis, Department of Mechanical Engineering, Pennsylvania State University.

Brasseur, J.G., Yeung, P.K. 1991 Large and small-scale coupling in homogeneous turbulence: analysis of the Navier-Stokes equation in the asymptotic limit. *Proc. Eighth Symposium on Turbulent Shear Flows*, Munich: 16-4-1 - 16-4-4.

Yeung, P.K., Brasseur, J.G. 1991 The response of isotropic turbulence to isotropic and anisotropic forcing at the large scales. *Phys. Fluids A* **3**: 884-897.

Brasseur, J.G. 1991 Comments on the Kolmogorov hypotheses of isotropy in the small scales. AIAA Paper No. 91-0230, AIAA Aerospace Sciences Meeting, Reno, Jan. 1991.

Brasseur, J.G., Lin, W.-Q. 1991 Structure and statistics of intermittency in homogeneous turbulent shear flow. *Advances in Turbulence 3*, Springer-Verlag, Heidelberg: 3-12.

B. Abstracts

Brasseur, J.G., Wang, Q. 1993 Locality in physical space, locality in Fourier-space, and the relationship between the two. *Bull. Amer. Phys. Soc.* **38** (12): p. 2228.

Wang, L-P., Brasseur, J.G. 1993 Contribution of Long-range Interactions to Small-scale Phase Changes in Isotropic Turbulence. *Bull. Amer. Phys. Soc.* **38** (12): p. 2243.

Brasseur, J.G. 1992 How should one view "large" and "small" scales in fully developed turbulence? *Bull. Amer. Phys. Soc.*, 37(10):1703.

Lin, W.-Q., Brasseur, J.G. 1992 Dynamics of small-scale structural development within turbulent shear flows. *Bull. Amer. Phys. Soc.*, 37(10):1776.

Brasseur, J.G., Wei, C.H. 1991 Spectral dynamics in high Reynolds number turbulence via triadic interactions. *Bull. Amer. Phys. Soc.* **36**(10): 2627.

Yeung, P.K., Brasseur, J.G. 1991 1991 Interscale dynamics in homogeneous turbulence: Fourier and physical space views. *Bull. Amer. Phys. Soc.* **36**(10): 2628.

Brasseur, J.G. 1990 The necessity of nonisotropy in the small scales: comments on the Kolmogorov hypotheses. *Bull. Amer. Phys. Soc.* **35** (10):2305.

Yeung, P.K., Brasseur, J.G. 1990 Response of isotropic turbulence to anisotropic forcing at the large scales. *Bull. Amer. Phys. Soc.* 35 (10):2255.

Lin, W.-Q., Brasseur, J.G. 1990 Kinematics and dynamics of intermittent regions in homogeneous turbulent shear flow. *Bull. Amer. Phys. Soc.* 35 (10):2268.

Wang, Q., Brasseur, J.G., Sreenivasan, K.R. 1990 Application of a 3D wavelet transform to vortical evolution in homogeneous turbulence. *Bull. Amer. Phys. Soc.* 35 (10):2254.

C. Papers In Preparation

Brasseur, J.G. & Lin, W-Q. Quantitative and graphical analysis of the intermittent structure of homogeneous turbulent shear flow using a new methodology.

Brasseur, J.G. & Lin, W-Q. Structure, statistics and dynamics of the small-scale vorticity field associated with the creation of anisotropic shear-flow turbulence from isotropic turbulence.

Wang, Q. & Brasseur, J.G. The relationship between scale and structure at the small scales in fully developed isotropic and anisotropic turbulence.

Wang, L-P., Brasseur, J.G., Chen, S. Phase interactions associated with large-small-scale couplings in isotropic turbulence.

Wang, L-P., Brasseur, J.G., Chen, S. Scale interactions between scalar and velocity modes in isotropic turbulence .

Wang, L-P., Brasseur, Chen, S., J.G., Wyngaard, J. Analysis of Kolmogorov's refined similarity hypothesis: I. small-scale velocity differences in isotropic turbulence.

Wang, L-P., Brasseur, J.G., Chen, S., Wyngaard, J. Analysis of Kolmogorov's refined similarity hypothesis: II. small-scale scalar differences in isotropic turbulence.

V. MEETINGS, SEMINARS, WORKSHOPS

A. Invited Papers and Workshops

June 1994 Invited one hour paper at the AIAA Fluid Dynamics Conference, Colorado Springs, Colorado, "The wavelet decomposition: locality in Fourier space, locality in physical space and the relationship between the two."

May 1994 Johns Hopkins University, "Interscale interactions in stationary vs. nonstationary nonequilibrium turbulence."

March 1994 National Center for Atmospheric Research, "Local similarity at the small scales in low Reynolds number isotropic turbulence."

March 1994 Lehigh University, "Structure and statistics of scalar evolution in the flat plate turbulent boundary layer using direct simulations."

July 1993 Invited paper at the Nonlinear Dynamics and Stochastic Processes Workshop, Center for Nonlinear studies, Los Alamos National Lab, "Interscale interactions in high Reynolds number turbulence."

Oct. 1992 Invited paper at SIAM Conference on Applications of Dynamical Systems, Salt Lake City, Utah, "The wavelet transform as a link between physical space and Fourier space."

July 1992 Ecole Centrale de Lyon, France, "Intermittency and anisotropy analysed using 3D wavelet transforms."

July 1992 Ecole Nationale Superieure, Grenoble, France, "Interscale interactions in high Reynolds number turbulence."

April 1992 CUNY/Levich Institute, "Issues in High Reynolds Number Turbulence."

March 1992 Los Alamos National Labs, "Turbulence Dynamics via Triadic Interactions."

March 1992	Brown University, "Combined Quantitative and Graphical Analysis of Intermittent Regions in Homogeneous Turbulence."
April 1992	Yale University, "Interscale Interactions in High Reynolds Number Turbulence."
Sept. 1991	First European Fluid Mechanics Conference, Cambridge, England. (Yeung.)
Sept. 1991	Ecole Centrale de Lyon, France, "Large and Small Scale Couplings in High Reynolds Number Turbulence."
June 1991	USA-French Workshop on Wavelets in Turbulence, Princeton University.
April 1991	Rutgers University, "Interactive Use of Graphical Imaging and Quantitative Measures in the Analysis of 3D Turbulence Data Sets."
March 1991	Pennsylvania State University, "Modification of Small Scale Structure by Large Scale Forcing."
Feb. 1991	University of Maryland, "Analysis of Intermittent Regions in Homogeneous Turbulent Shear Flow."
Nov. 1990	43rd Annual Meeting of the APS Division of Fluid Dynamics, Cornell University, NY, (7 papers).
Sept. 1990	Invited participant and session recorder for 1990 Workshop entitled "New Approaches to Experimental Turbulence Research," Princeton University, New Jersey.
Aug. 1990	Invited participant at 1990 "Boundary Layer Structure Workshop," NASA-Langley, Virginia.
May 1990	Cornell University: "Characteristics of Intermittent Regions in Homogeneous Turbulent Shear Flow."

B. Meetings

August 1993	AFOSR Contractors Meeting, Flagstaff, AZ (attendee.)
March 1993	Multiscale Stochastic Processes Analyzed using Multifractals and Wavelets, Cambridge University, England (2 papers, and conference organizer along with J.C. Vassilicos, P. Flandrin and J. Hunt).
March 1993	Arizona State, International Conference on near-wall turbulent flows. (1 paper)
Nov. 1992	45th Annual Meeting of the APS Division of Fluid Dynamics, Florida State University, FL (5 papers relating to this program).
June. 1992	AFOSR/ONR Contractors Meeting, IIT, Chicago, IL (one presentation).
June 1992	The 4th European Turbulence Conference, Delft, The Netherlands. (1 paper)
Nov. 1991	44th Annual Meeting of the APS Division of Fluid Dynamics, Stanford, CA (1 paper).
Sept. 1991	Eighth Symposium on Turbulent Shear Flows, Munich, Germany. (1 paper)
Sept. 1991	First European Fluid Mechanics Conference, Cambridge, England. (1 paper)
June 1991	USA-French Workshop on "Wavelets and Turbulence," Princeton University (1 presentation)
April 1991	AFOSR Contractor's Meeting, Ohio State, (2 presentations)
Jan. 1991	AIAA 29th Aerospace Sciences Meeting, Reno, Nevada (2 papers).

Nov. 1990	43rd Annual Meeting of the APS Division of Fluid Dynamics, Cornell University, NY, (5 papers relating to this program).
July 1990	The 3rd European Turbulence Conference, Stockholm, Sweden (1 paper)